JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 101, NO. B8, PAGES 17,569–17,576, AUGUST 10, 1996

Reply

S. E. Ingebritsen
U.S. Geological Survey, Menlo Park, California

D. R. Sherrod
U.S. Geological Survey, Vancouver, Washington

R. H. Mariner
U.S. Geological Survey, Menlo Park, California

We appreciate the opportunity to elucidate our thinking with respect to the issues raised by *Blackwell and Priest* [this issue; hereinafter BP]. Their commentary criticizes our analysis of heat flow data from the north-central Oregon Cascades. In their view, we have relied too heavily on low-quality heat flow data, misinterpreted the heat flow data from some key drill holes, and contoured the resulting data set in a misleading or overly detailed fashion. They also disagree with our analysis of the relation between the heat flow and gravity data and question our attempts to estimate crustal permeability. Here we will show that the differences between our heat flow map and that of BP do not depend on the details of the data set but do depend fundamentally on how the data are interpreted and contoured. We will also briefly rebut their criticism of the permeability and gravity-heat flow discussions.

Our own conclusions regarding hydrothermal activity in the Oregon Cascades depend not only on heat flow data but also on a wealth of contextual geological and geophysical information. The study of conductive and advective heat flow was part of an interdisciplinary effort by the U.S. Geological Survey to reassess the geothermal resources of the U.S. part of the Cascade Range. The work in north central Oregon also included detailed geologic mapping, analyses of water chemistry from about 800 sites, geophysical surveys, stream gaging, and numerical simulations of groundwater flow and heat transport. We concluded that high heat flow values west of the Quaternary arc can in fact be explained in terms of lateral outflow of groundwater heated by discrete igneous centers along a relatively narrow zone of magmatism. This "lateral flow" model has contributed to reduced estimates of the undiscovered geothermal resource [e.g., *Muffler and Guffanti*, 1995] but defines a clearer geothermal exploration target than alternative models assuming a broad midcrustal heat source.

Differences With Respect to Individual Heat Flow Data

BP devote much of their commentary to a detailed, hole-by-hole criticism of our interpretation of the heat flow data. We will not engage in a similarly detailed rebuttal; such an approach would only obscure the fundamental differences between our respective analyses. In the following section we will highlight those differences by focusing on the "correct" data set endorsed by BP (their Figure 1). However, before proceeding with that approach, we do feel compelled to briefly defend some of our own individual heat flow interpretations.

The choice of thermal conductivity in the Breitenbush Hot Springs region alone accounts for about one-third of the sites with major differences in heat flow values. Our heat flow estimates from 12 SUNEDCO holes in the Breitenbush Hot Springs area are significantly higher than those of BP, as noted in their Table 2. The reason is that we used a higher thermal conductivity value than BP (1.50 or 1.65 W m^{-1} K^{-1} versus 1.38 W m^{-1} K^{-1}), based on the lithology encountered in the drill holes and the mean thermal-conductivity values for Cascade rocks of similar age and lithology. BP's value of 1.38 W m^{-1} K^{-1} for the holes in >7 Ma lava flows is more than two standard deviations below the mean thermal conductivity value reported for such rocks (the mean$\pm$standard deviation values for 14 holes drilled in >7 Ma lava flows in the Cascades are 1.65$\pm$0.13 W m^{-1} K^{-1} [*Ingebritsen et al.*, 1988, pp. 34-39; 1994, pp. 37-39]). Both our thermal conductivity choices and the lower value chosen by BP are estimated values and thus subject to large errors, but our own choices are clearly reasonable.

Most of the other differences involve data from sites with obvious intraborehole and/or extraborehole fluid flow, which are commonly subject to varying interpretations. Our consistent approach to interpreting heat flow from such sites was to choose conductive or quasi-conductive intervals below the depth of obvious hydrologic disturbance. We agree that there are reasonable alternatives in a number of instances. For example, several of the temperature profiles shown in BP's Figure 2 can very reasonably be interpreted in terms of intraborehole flow. However, it seems likely to us that the three temperature profiles (not shown) from 16S/5E/30 (see their Table 2) are affected by extraborehole flow, that is, flow in the adjacent porous medium. These shallow (<85 m) drill holes are sited on or near the floodplain of the South Fork of the McKenzie River and are completed mainly in permeable river alluvium. The temperature profiles show varying degrees of downward curvature of the type associated with downward/lateral fluid flow. In this shallow, permeable environment it seems quite likely that extraborehole groundwater flow could cause real local differences in the conductive component of heat flow. Our approach to these data was to calculate a heat flow value for the deeper, linear section of each

Paper number 96JB01506.

of the three profiles. The average of these values (75 mW m^{-2}) is actually quite similar to the value that BP assign to the site (70 mW m^{-2}).

The drill hole at 6S/7E/30 (their Table 2) should probably not have been included in a compilation of regional heat flow, as it is located only a few tens of meters from a group of hot spring orifices (Austin Hot Springs) that accounts for about 88 MW of advective heat loss. However, the bottom 147 m of the temperature profile from this 293-m-deep drill hole is linear and is the basis for our own heat flow estimate. The BP value of >300 mW m^{-2}, based on the 0- to 10-m-depth interval, is a reasonable estimate of heat loss to the surface, whereas our own value is a more reasonable guess at the deeper heat flow regime (note that BP's Figure 3b shows data from only the top 40 m of this drill hole).

In their discussion of data from sites with obvious intraborehole and/or extraborehole fluid flow, BP emphasize matching "... the extrapolated surface temperature of the temperature-depth curve to the mean annual surface temperature of the area ..." We agree that this is often a valuable approach but maintain that it is not necessarily appropriate in areas with pervasive hydrologic disturbances. We shall return to this point in the section on hydrogeologic considerations.

Instead of further belaboring our own reasoning with respect to the individual sites we invite interested readers to refer to earlier publications. Our previous tabulations of the heat flow data include all of our own heat flow estimates and all of the estimates published by Blackwell and colleagues, along with the supporting data such as temperature profiles, so that the source(s) of any disagreement will be clear [*Ingebritsen et al.*, 1988, pp. 7-33 and 101-205; 1994, pp. 73-86]. As mentioned by BP, our tabulations omitted certain heat flow estimates reported by *Blackwell et al.* [1990]. This was a conscious omission. Our tabulations were restricted to public domain data, and the temperature-depth data upon which the omitted estimates were based had not been released. However, in the analysis that follows we include all of the heat flow estimates endorsed by BP.

How to Contour the Heat Flow Data?

A basic premise of the BP commentary is that differences between our heat flow map of the north central Oregon Cascades and their own map (their Figure 1) result mainly from our misinterpretation of key data. In fact, the differences between the heat flow maps depend fundamentally on how the data are contoured and not on the details of the data set. This can be shown by treating our own version of the heat flow data set and BP's "correct" version in exactly the same manner.

Our own earlier heat flow maps (e.g., Figure 1) were based on the larger heat flow data set tabulated by *Ingebritsen et al.* [1994, pp. 73-86]. Values of heat flow were estimated at the nodal points of a 5-km by 5-km grid by calculating an inverse-distance-squared weighted average of the nearest data points in each quadrant. Heat flow was contoured from the gridded surface. The gridding and contouring were done with SURFER™, a commercial contouring program. Certain data were excluded in the gridding; for example, those from drill holes identified as nearly isothermal or advectively disturbed [see *Ingebritsen et al.*, 1994, p. 36]. The contours were not extended into the younger volcanic rocks (younger than about 7 Ma) because, as BP note, drill holes in those rocks generally show low-to-zero heat flow to the depths of conventional measurements (100-200 m) as the result of copious groundwater recharge.

The version of the heat flow data set regarded as correct by BP excludes or reinterprets many of the data used to generate our contour map. Nevertheless, applying the same contouring algorithm to BP's version of the data set results in a set of contours (Figure 2) similar to our own (Figure 1) and very different from BP's (their Figure 1). Both of the maps generated by the inverse-distance-squared algorithm show lobate heat flow highs associated with hot spring groups and substantially lower values between hot springs, whereas the BP map is dominated by a north-south striking heat flow gradient west of the Quaternary volcanic arc.

The question then arises as to whether any objective algorithms can give rise to contours more similar to BP's. It seems reasonable to assume that the Cascade Range possesses N-S anisotropy, and by using a kriging algorithm and invoking a severe (10:1) N-S anisotropy we were able to generate a set of contours (Figure 3) that shows a similar steep, linear north-south striking heat flow gradient west of the Quaternary arc. We regard this set of contours as being in qualitative agreement with those of BP. The kriged heat flow pattern east of the heat flow gradient is more complex than in BP's map (compare Figure 3 with their Figure 1), with the large, uniform area of 100 mW m^{-2} heat flow broken into warmer and cooler subareas. However, the data coverage over much of this area is poor. BP's tacit assumption that heat flow beneath the Quaternary arc is generally $\geq$100 mW m^{-2} seems reasonable to us and would supersede much of the objective contouring in this area.

In 1988-1991 the U. S. Geological Survey drilled four holes west of the Quaternary arc in an effort to test the alternative ways of contouring the heat flow data. The holes were drilled in areas where the uniform heat flow contours of BP (their Figure 1) predicted relatively high heat flow, but where heating due to regional-scale, topographically driven groundwater flow seemed unlikely [*Ingebritsen et al.*, 1993]. The resulting heat flow data are of higher quality than most heat flow data from the region because the the drill hole annuli were grouted, temperatures were monitored to equilibrium, and abundant thermal conductivity data were acquired. *Blackwell and Priest* [1996] include these new heat flow values in their "correct" data set, and BP cite them as supporting their preferred model of the thermal structure, despite the fact that the measured heat flows (Figure 2: 76$\pm$5 mW m^{-2}) were lower than the values predicted by interpolation from their own heat flow map (95$\pm$7 mW m^{-2}).

In hindsight, our attempt to test the validity of the contours through such a limited test-drilling program was doomed to fail. Both the BP contours and the contours generated by the kriging algorithm are highly smoothed and heavily weighted in the N-S dimension, such that the contours no longer honor many of the individual heat flow data (see BP's Figure 1). Given this approach to contouring, it would be nearly impossible to test the validity of the contours by simply drilling a few new holes in strategic locations. In contrast, the inverse-distance-squared contouring algorithm, which is more akin to how one might contour the data by hand, honors nearly all of the data points. Given this approach, a few new heat flow values in undersampled locations can result in substantially different contours.

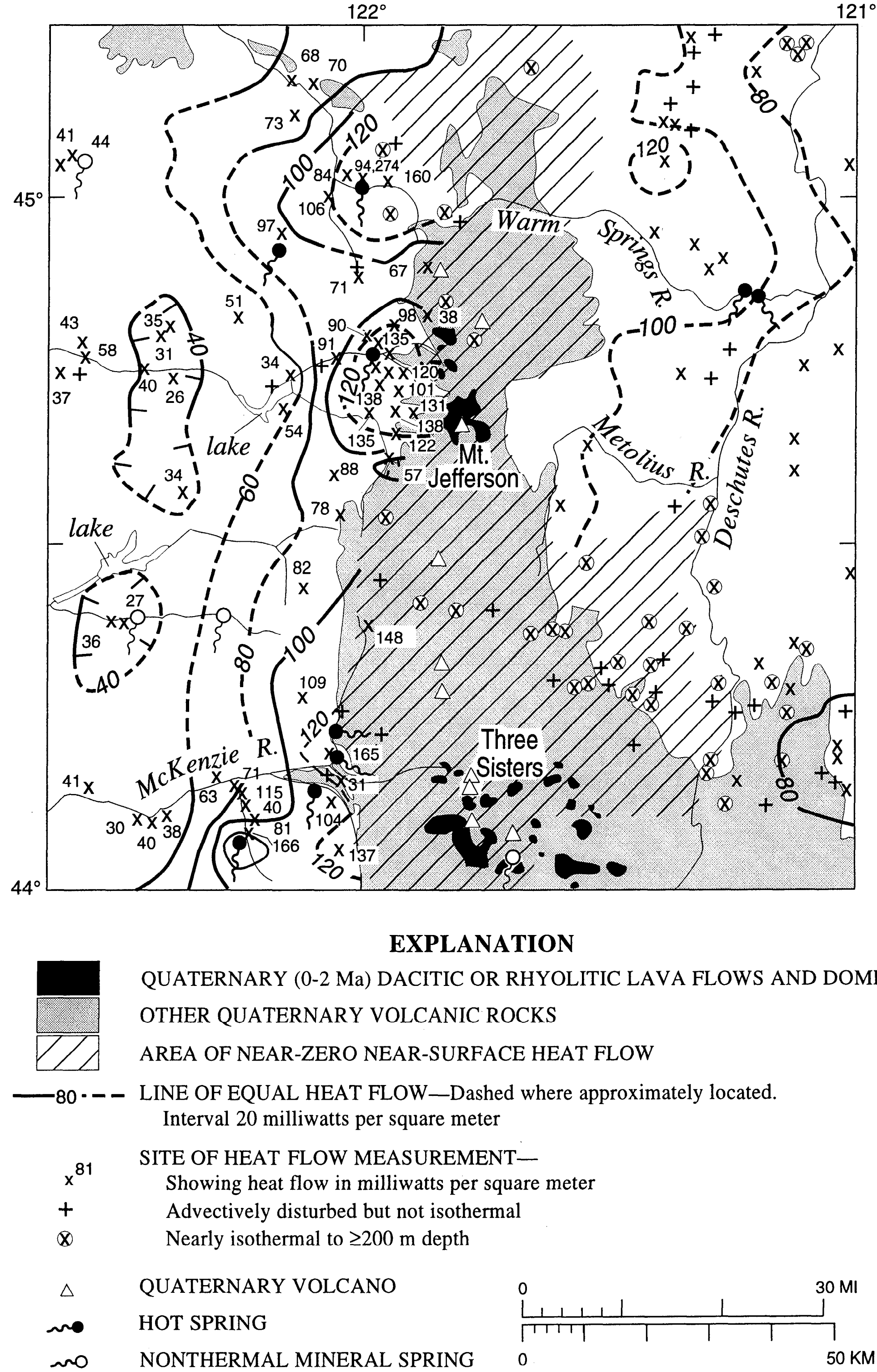
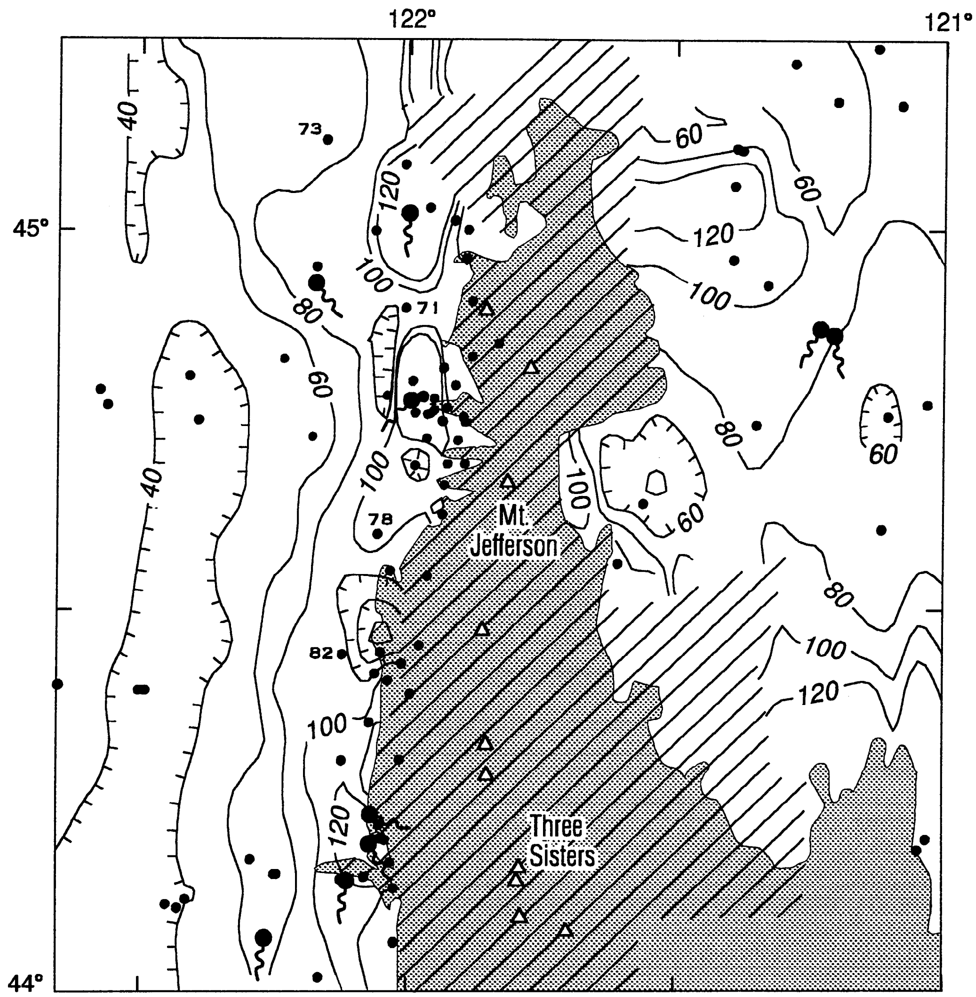


Figure 1. Heat flow map from *Ingebritsen et al.* [1993]. Information about individual sites is given by *Ingebritsen et al.* [1994, pp. 73-86].

Hydrogeologic Considerations

Some of the differences between our approach and that of BP likely stem from our differing backgrounds and perspectives. BP approached the data from a crustal heat flow perspective. In the tradition of that discipline, they attempted to extract a midcrustal signal from a noisy data set containing near-surface perturbations such as groundwater flow. In contrast, we approached the data from a hydrogeologic perspective; our main interest is in those perturbations and what they reveal about patterns of fluid circulation. From that standpoint, even the advectively disturbed holes are of interest.



EXPLANATION

QUATERNARY VOLCANIC ROCKS

AREA OF NEAR-ZERO NEAR-SURFACE HEAT FLOW

—*120*— LINE OF EQUAL HEAT FLOW – Interval 20 milliwatts per square meter

• SITE OF HEAT FLOW MEASUREMENT REGARDED AS CORRECT BY B&P. Four new heat-flow sites described by Ingebritsen et al. (1993) are labelled with values in milliwatts per square meter. See Blackwell and Priest (this issue, Fig. 1) for other heat flow values

Δ QUATERNARY VOLCANO

HOT SPRING

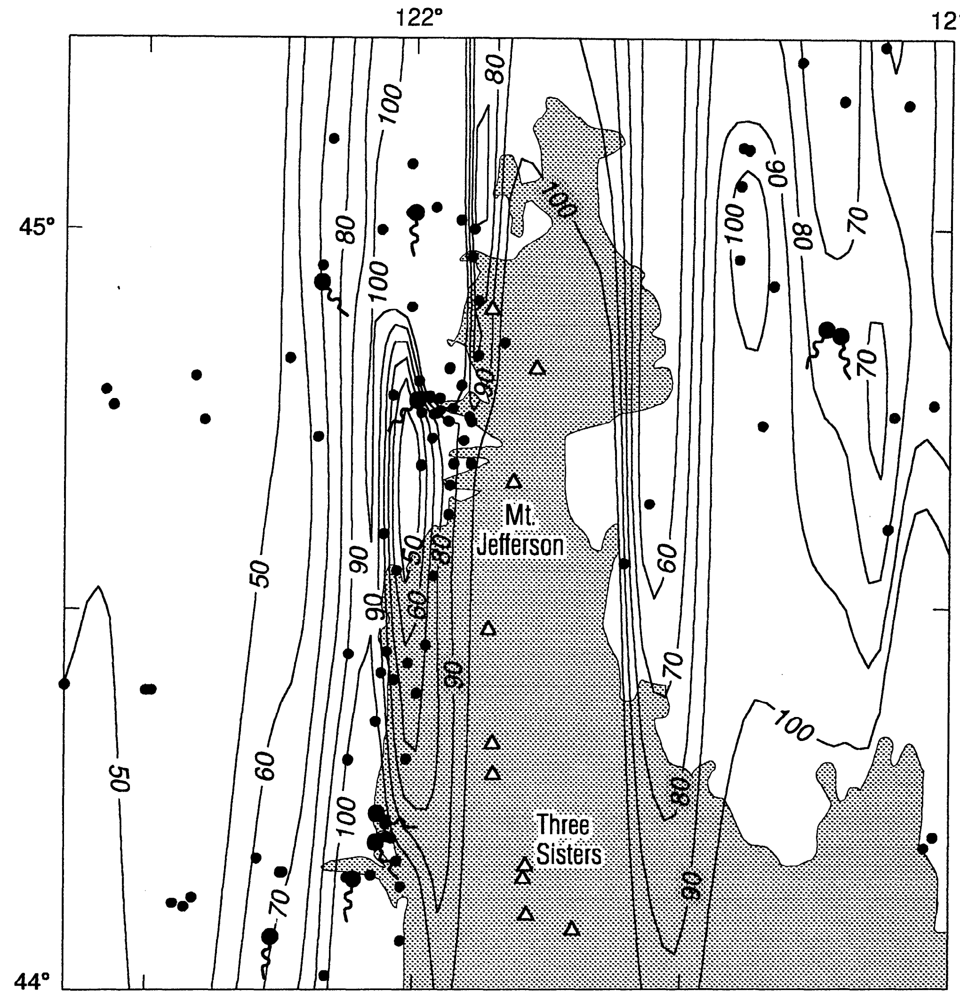
0 30 MI

0 50 KM

Figure 2. Heat flow map generated from the data set regarded as correct by BP, using the same contouring algorithm that was used to generate our Figure 1. The four labeled values are data from *Ingebritsen et al.* [1993] that BP cite as supporting their version of the thermal regime, and other values are as shown in BP (their Figure 1).

We still frankly doubt that it is possible to see through the effects of groundwater flow on these particular data. In the Cascade Range, copious precipitation (locally >2.5 m yr^{-1}), extensive exposures of permeable volcanic rocks, and large topographic gradients (~1:10) combine to ensure vigorous groundwater flow, at least at shallow depths. Groundwater recharge rates exceed 1 m yr^{-1} over large areas of the Cascades [*Ingebritsen et al.*, 1992, 1994, pp. 16-18], whereas vertical flow rates of only a few centimeters per year are sufficient to grossly distort the Earth's thermal field [e.g., *Bredehoeft and Papadopolous*, 1965].

The abrupt heat flow gradient mapped by BP west of the Quaternary arc (see their Figure 1) depends largely on a set of local heat flow anomalies associated with hot spring areas.



EXPLANATION

QUATERNARY VOLCANIC ROCKS

—120— LINE OF EQUAL HEAT FLOW – Interval 20 milliwatts per square meter

• SITE OF HEAT FLOW MEASUREMENT REGARDED AS CORRECT BY BLACKWELL AND PRIEST (this issue)–See Blackwell and Priest (this issue, Fig. 1) for heat flow values

△ QUATERNARY VOLCANO

HOT SPRING

0 30 MI

0 50 KM

Figure 3. Heat flow map generated from the data set regarded as correct by BP. Here we attempt to replicate BP's contours by using a kriging algorithm and weighting the data much more heavily in the N-S dimension than in the E-W dimension (a 10:1 anisotropy, such that a datum that is 10 km north or south of a grid point is weighted as heavily as a datum that is 1 km east or west of the grid point).

The hot springs occur across a narrow elevation range (440-680 m) in deeply incised valleys that capture regional groundwater flow from the Quaternary arc. They occur at roughly the same longitude, so that when the local heat flow data are sufficiently smoothed and weighted in a north-south direction, a continuous heat flow gradient appears (e.g., Figure 3, or BP's Figure 1). When the data are not smoothed and weighted, a more lobate set of heat flow anomalies emerges (Figures 1 and 2).

Blackwell et al. [1982] considered and rejected a "lateral flow" model that explained the heat flow gradient west of the Quaternary arc in terms of groundwater flow toward the hot springs. We chose to resurrect this model for three reasons. First, stable isotope data indicate that the hot springs are likely recharged in the Quaternary arc, at elevations of about 1300-1900 m [e.g., *Ingebritsen et al.*, 1989, Figure 2]. Second, a heat budget analysis showed that the heat transferred from the Quaternary arc via groundwater flow is sufficient to account for the anomalously high heat flow observed west of the arc [*Ingebritsen et al.*, 1989, 1994, pp. 41-44]. Finally, we were attracted to a model that did not require a widespread midcrustal heat source extending >20 km west of the area of Quaternary volcanism.

BP suggest that heat flow measurements in deeper holes prove the reliability of heat flow values determined in shallow holes. We hold a nearly opposite view and cite the temperature-depth data shown in Figure 4 as the basis for our skepticism. Figure 4 shows all of the deep (>460-m depth) holes in the study area. Every hole exhibits major, hydrologically forced changes in temperature gradient (Figure 4a),

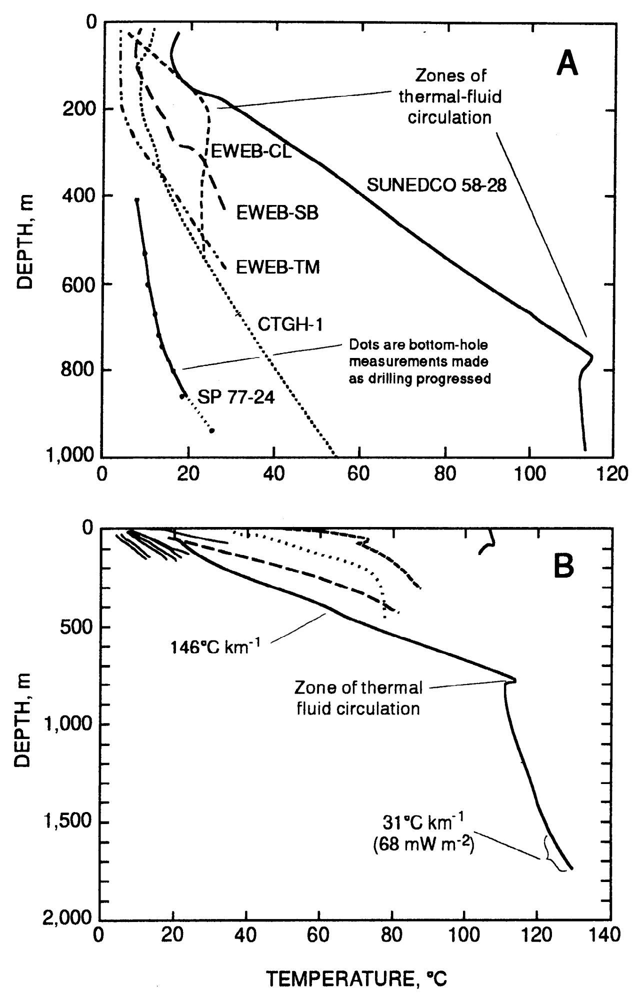


Figure 4. (a) Temperature-depth data from relatively deep (>460 m) drill holes in the study area. Heat flow values from EWEB-SB, EWEB-TM, and EWEB-CL were reported by *Blackwell et al.* [1982], CTGH-1 and SUNEDCO 58-28 by *Blackwell and Baker* [1988], and SP 77-24 by *Blackwell* [1992]. (b) Temperature-depth profiles from drill holes collared in >7 Ma rocks in the Breitenbush Hot Springs area [*Blackwell and Baker*, 1988; *Blackwell et al.*, 1990; *Ingebritsen et al.*, 1988]. Seventeen shallow holes (<500 m deep) have high gradients that generally correspond to heat flows >110 mW m^{-2}. However, a similar gradient in the upper part of the deepest hole (SUNEDCO 58-28) changes abruptly below a zone of thermal fluid circulation in >20 Ma rocks at ~800 m depth, suggesting that the gradients in the shallow holes are also controlled by groundwater flow.

such that the temperature gradients measured in the depth range of a typical heat flow hole (<200 m) are substantially different than those observed at greater depths. Despite BP's argument that older (>5 Ma) volcanic rocks have negligible permeability, temperature reversals are seen to occur due to thermal fluid circulation in such rocks. For example, in the Breitenbush Hot Springs area, the conductive gradients seen in numerous 150- to 500-m-deep drill holes are likely controlled by a thermal aquifer in >20 Ma rocks at ~800-m depth (Figure 4b) (see *Priest et al.* [1987] for a description of the thermal aquifer). Because of the paucity of deep drill holes in the older rocks, it is impossible to say whether such disturbances are widespread. However, on the basis of the existing set of observations in the vicinity of the heat flow transition (Figure 4), we find it imprudent to project shallow temperature profiles from this region to midcrustal depths.

It is enlightening to revisit BP's emphasis on matching "... the extrapolated surface temperature of the temperature-depth curve to the mean annual surface temperature of the area ..." in the context of the deeper data shown in Figure 4a. The deeper, linear parts of the EWEB-TM and CTGH-1 profiles project to unreasonably low surface temperatures of about -10 °C. The quasi-conductive lowermost segment of SP 77-24 extrapolates to an even lower surface temperature of about -50°C. Yet these data constitute our only information about thermal conditions below the zone of copious groundwater recharge in this part of the Quaternary arc, and BP rate EWEB-TM and CTGH-1 as A and B quality heat flow sites, respectively. In areas of vigorous groundwater flow, one cannot require all gradients to extrapolate to mean surface temperature without dismissing potentially valuable information.

Permeability Structure

We feel that BP overstate our differences with respect to crustal permeabilities and the associated likelihood of regional groundwater flow. In our simulations of heat and fluid flow, we invoked bulk permeabilities of $\geq 10^{-14}$ m^2 for <2 Ma volcanic rocks, 1-5x10^{-16} m^2 for 4-18 Ma rocks, and $\leq 10^{-17}$ m^{-2} for >18 Ma rocks [*Ingebritsen et al.*, 1992, p. 4610] and recognized that only the upper and lower values were usefully constrained by the heat flow data. We also recognized that substantially higher permeabilities must occur in the very near surface (<50 m depth) in order to accommodate the large rates of groundwater recharge indicated by water budget calculations. However, these higher values were not used in the simulations because we were simulating a large crustal thickness (5-7 km) and because such a shallow "skin" effect should not be reflected in the heat flow data, nearly all of which are based on measurements from greater depths. Finally, we noted, like BP, that discrete zones of high permeability must exist in the older rocks, in order to explain temperature gradient changes such as those seen at SUNEDCO 58-28 and EWEB-CL (Figure 4).

BP are skeptical of regional groundwater flow between the Quaternary arc and the hot springs, citing topographic barriers and structural discontinuities as well as low permeabilities at depth. It was for this reason that we chose to simulate two cross sections through the Cascade Range: one in the Breitenbush area (approximately 44°47'N), where no major topographic or structural discontinuities lie between the Cascade crest and the hot springs; and one in the upper McKenzie River area (approximately 44°05'N), where both topographic and structural barriers do exist. Because of the large overall topographic gradient (~1:10), transmissivities of ~1 darcy meter are sufficient in both areas to transfer heat from the Quaternary arc to the hot springs at the observed rate of ~1 MW km^{-1} of arc length. The Breitenbush observations can be explained in terms of lateral flow at ~1 km depth, but advection-dominated simulations of the McKenzie River section required ~1 darcy meter transmissivities to occur at depths of several kilometers; groundwater flow at shallower depths is indeed interrupted by faults and associated topographic divides. Only about 0.2% of the groundwater recharged in the Quaternary arc must circulate to depth in order to sustain lateral heat transfer at the observed and simulated rate of ~1 MW km^{-1} of arc length.

Quantitative data regarding the deep permeability structure are critical to a fuller understanding of hydrothermal circulation but are essentially nonexistent. Our own estimates allowed us to match the thermal observations and are consistent with measurements in other volcanic environments. For instance, *Manga* [1996] modeled the discharge characteristics of springs in a part of the Oregon Cascade Range just south of our study area by assigning a near-surface (<100-m-depth) permeability of 10^{-11} m^2. Older and more deeply buried volcanic rocks are typically less permeable; several lines of evidence suggest that permeability at depth in the rift zones of Kilauea volcano is $<10^{-15}$ m^2 [*Ingebritsen and Scholl*, 1993], whereas the average of 21 pump test measurements on fresh, near-surface Hawaiian basalts is 2×10^{-10} m^2 [*Williams and Soroos*, 1973]. A similar range of permeabilities is observed in Iceland, with reported values ranging from around 10^{-16} m^2 in "unproductive wells in Tertiary formations" to 10^{-11} to 10^{-9} m^2 in post glacial lavas [*Arnorsson*, 1995, p. 612].

Heat Flow and Gravity

Blackwell and colleagues prefer to explain the heat flow gradient west of the Quaternary arc in terms of a midcrustal heat source related to magmatic intrusion. Their major argument in support of a wide midcrustal heat source has been a perceived correlation between their heat flow and gravity gradients, both of which were interpreted to result from a midcrustal zone of intrusion [e.g., *Blackwell et al.*, 1982; 1990]. Our simplistic approach to testing this correlation was to plot heat flow values versus various permutations of the gravity data (Bouguer, wavelength-filtered residual, isostatic residual, upward continued isostatic residual). We found that, outside of the Mount Hood area, the point-by-point heat flow-gravity correlation was weak to nonexistent [*Ingebritsen et al.*, 1992, Figure 19].

BP imply that this lack of correlation was due to our flawed choice of heat flow data. It is straightforward to show that this is not the case; carrying out the same analysis with BP's "correct" heat flow data gives very nearly the same result.

The point is moot, however. The previous analyses by *Blackwell et al.* [1982; 1990] and us are both largely superseded by the recent analysis of *Blakely* [1994], which indicated that both the gravity and heat flow gradients must be shallow rooted (<2.5 km and <5 km, respectively). In our view, the shallowness of the causal heat and mass distributions could both be related to lateral flow of heated groundwater confined to a relatively shallow (<2.5 km) crustal section of low-density/high-porosity rocks. The shallow source for the gravity gradient (as shallow as 0.7 km along one east-west profile) cannot plausibly be related to magmatic intrusion.

In their commentary, BP remind us of the high-quality heat flow data obtained by *Lewis et al.* [1988] in British Columbia. These data also show a steep north trending gradient west of the Quaternary volcanic arc, and BP cite them in support of a deeper heat source. Superposition of the Oregon and British Columbia gradients reveals that they are similarly steep and therefore share a similarly shallow source depth.

Discussion

The thermal signature of volcanic arcs worldwide appears to consist of a forearc low, a rather abrupt transition to high heat flow seaward of the arc, and a broad region of elevated heat flow extending into the backarc region. In the north central Oregon example, topographically driven regional groundwater flow introduces some complexity to the forearc-arc heat flow transition, broadening its surface expression. Within the volcanic arc itself, near-surface conductive heat flow is almost completely suppressed by the copious groundwater recharge. It seems likely that deeper heat flow patterns within the arc are quite complex, due to advection by magma as well as groundwater.

We have always been careful not to completely discount the model for the deeper thermal structure favored by Blackwell and colleagues and do not regard our own version of the heat flow map (Figure 1) as a proxy for the deep thermal structure, but rather as a prediction of the thermal conditions that might be expected at the depths of conventional measurements. In fact, our own numerical modeling experiments showed that the existing thermal observations, taken alone, can be explained either in terms of (1) a laterally extensive midcrustal heat source or (2) a narrower, spottier deep heat source that is confined to the Quaternary arc and is flanked by relatively shallow heat flow anomalies caused by regional groundwater flow [*Ingebritsen et al.*, 1992]. Although certain of the thermal observations do require substantial lateral heat transfer via groundwater flow, including some flow in the older (>7 Ma) volcanic rocks (e.g., Figure 4, SUNEDCO 58-28 and EWEB-CL), the deeper thermal structure will not be uniquely determined without additional deep drilling.

Our preference for the alternative, "lateral flow" model is based on (1) the large rates of advective heat transport associated with hot spring discharge west of the Quaternary arc in this area (~1 MW km^{-1} arc length), combined with (2) isotopic data indicating that the hot springs are likely recharged within the Quaternary arc; (3) a heat-budget analysis showing that the heat transferred from the Quaternary arc via groundwater flow is sufficient to account for the anomalously high heat flow observed west of the arc; (4) simple quantitative analyses which indicate shallow source-depths for the gravity and heat flow gradients west of the Quaternary arc [*Blakely*, 1994]; (5) the fact that most of the hot springs occur on or near the heat flow/gravity gradient; and (6) the actual distribution of the Quaternary volcanic centers. Further, as we have shown here, (7) objective contouring of either version of the heat flow data set (ours or BP's) gives rise to a heat flow pattern consistent with the "lateral flow" model (Figures 1 and 2).

Acknowledgments. We thank Rick Blakely, Patrick Muffler, and John Sass for thoughtful colleague reviews and Elizabeth Colvard for assistance with contouring and drafting the figures.

References

Arnorsson, S., Geothermal systems in Iceland: Structure and conceptual models, II, Low-temperature areas, *Geothermics, 24*, 603-629, 1995.

Blackwell, D.D., Geothermal and geophysical data from the Santiam Pass 77-24 well, *Oreg. Dep. Geol. Miner. Ind. Open File Rep., O-92-3*, 37-52, 1992.

Blackwell, D.D., and S.L. Baker, Thermal analysis of the Austin and Breitenbush geothermal systems, Western Cascades, Oregon, *Oreg. Dep. Geol. Miner. Ind. Open File Rep., O-88-5*, 47-62, 1988.

Blackwell, D.D., and G.R. Priest, Comment on "Heat flow from four new research drill holes in the Western Cascades, Oregon, U.S.A.", *Geothermics, 25*, in press, 1996.

Blackwell, D.D., and G.R. Priest, Comment on "Rates and patterns of groundwater flow in the Cascade Range volcanic arc, and the effect on subsurface temperatures", *J. Geophys. Res.*, this issue.

Blackwell, D.D., R.G. Bowen, D.A. Hull, J. Riccio, and J.L. Steele, Heat flow, arc volcanism, and subduction in northern Oregon, *J. Geophys. Res., 87*, 8735-8754, 1982.

Blackwell, D.D., J.L. Steele, M.K. Frohme, C.F. Murphy, G.R. Priest, and G.L. Black, Heat flow in the Oregon Cascade Range and its correlation with regional gravity, Curie point depths, and geology, *J. Geophys. Res., 95*, 19,475-19,494, 1990.

Blakely, R.J., Extent of partial melting beneath the Cascade Range, Oregon: Constraints from gravity anomalies and ideal-body theory, *J. Geophys. Res., 99*, 2757-2773, 1994.

Bredehoeft, J.D., and I.S. Papadopolous, Rates of vertical groundwater movement estimated from the Earth's thermal profile, *Water Resour. Res., 1*, 325-328, 1965.

Ingebritsen, S.E., and M.A. Scholl, The hydrogeology of Kilauea volcano, *Geothermics, 22*, 255-270, 1993.

Ingebritsen, S.E., R.H. Mariner, D.E. Cassidy, L.D. Shepherd, T.S. Presser, M.K.W. Pringle, and L.D. White, Heat-flow and water-chemistry data from the Cascade Range and adjacent areas in north-central Oregon, *U.S. Geol. Surv. Open File Rep., 88-702*, 205 pp., 1988.

Ingebritsen, S.E., D.R. Sherrod, and R.H. Mariner, Heat flow and hydrothermal circulation in the Cascade Range, north-central Oregon, *Science, 243*, 1458-1462, 1989.

Ingebritsen, S.E., D.R. Sherrod, and R.H. Mariner, Rates and patterns of groundwater flow in the Cascade Range volcanic arc, and the effect on subsurface temperatures, *J. Geophys. Res., 97*, 4599-4627, 1992.

Ingebritsen, S.E., M.A. Scholl, and D.R. Sherrod, Heat flow from four new research drill holes in the Western Cascades, Oregon, *Geothermics, 22*, 151-163, 1993.

Ingebritsen, S.E., R.H. Mariner, and D.R. Sherrod, Hydrothermal systems of the Cascade Range, north-central Oregon, *U.S. Geol. Surv. Prof. Pap., 1044-L*, 86 pp., 1994.

Lewis, T.J., W.H. Benkowski, E.E. Davis, R.D. Hyndman, J.G. Souther, and J.A. Wright, Subduction of the Juan de Fuca plate: Thermal consequences, *J. Geophys. Res., 93*, 15,207-15,225, 1988.

Manga, M., Hydrology of spring-dominated streams in the Oregon Cascades, *Water Resour. Res.*, in press, 1996.

Muffler, L.J.P., and M. Guffanti, Are there significant hydrothermal resources in the U.S. portion of the Cascade Range?, paper presented at 20th Workshop on Geothermal Reservoir Engineering, Stanford Univ., Stanford, Calif., Jan. 24-26, 1995.

Priest, G.R., N.M. Woller, and M.L. Ferns, Geologic map of the Breitenbush River area, Linn and Marion Counties, Oregon, scale 1:62,500, *Oreg. Dep. Geol. Miner. Ind. Geol. Map Ser., GMS-46*, 1987.

Williams, J.A., and R.L. Soroos, Evaluation of methods of pumping test analysis for application to Hawaiian aquifers, *Technical Report 20*, 159 pp., Univ. of Hawaii Water Resour. Res. Cent. Honolulu, 1973.

S. E. Ingebritsen and R. H. Mariner, U. S. Geological Survey, MS 439, 345 Middlefield Road, Menlo Park, CA 94025. (e-mail: seingebr@usgs.gov; rmariner@usgs.gov)

D. R. Sherrod, U. S. Geological Survey, 5400 MacArthur Blvd., Vancouver, WA 98661. (e-mail: dsherrod@usgs.gov)

(Received May 1, 1996; accepted May 8, 1996.)